TITLE: Results of Selected Experiments Involving Supercavitating Flows

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SUMMARY

For much of the last decade, the Naval Undersea Warfare Center (NUWC) Division, Newport, Rhode Island, has conducted basic research and development involving supercavitating projectiles. Under this program, the theory of high-Mach-number underwater flows has been investigated and first-principles modeling of cavity development and projectile dynamics and stability have all been addressed.

To support these analytical efforts, a sophisticated experimental program has similarly matured. The NUWC Division Newport Supercavitating High-Speed Bodies (SHSB) Test Range has been designed to safely test underwater gun-launched projectiles traveling in excess of the speed of sound in water. This range was installed as an upgrade to a facility originally designed as a tow tank for testing tactical scale undersea vehicles. Currently the test range is 17 m long and approximately 4 m deep. Armor plates positioned ~1.5 m apart ensure that even unstable projectile trajectories are confined to the range.

This lecture describes the experimental facility and the tests performed there through the end of the author's tenure at NUWC circa December, 1998. A description of the test range, its instrumentation suite, and the extensive photographic capabilities developed to capture these high-speed projectiles are discussed. A summary of the experimental milestones through December, 1998, is also presented.

INTRODUCTION

An underwater test range was constructed in the NUWC tow tank and has been used in over 50 supercavitating high-speed projectile tests in support of the Supercavitating High-Speed Bodies (SHSB) program. This program involves basic research into very high-speed undersea projectiles. Application of supercavitation drag reduction at munitions scales can result in projectiles capable of supersonic velocities (exceeding 1500 m/s in water) over short ranges. The tests were executed by the SHSB Test Team at NUWC Division, Newport, Rhode Island, USA.

Important milestones in this program included the successful demonstration of 20-mm gun-launched underwater high-speed projectiles at the Langley Tow Tank in Hampton, Virginia in 1994 and the construction and test of an underwater test range for 30-mm gun-launched subsonic and supersonic projectiles at NUWC in 1996. The NUWC facility uses a 30-mm underwater gun launcher and is fully instrumented to provide the high-speed data and images necessary to conduct a comprehensive research program.

The experiments described here were performed in the NUWC building 1246 Tow Tank using a high-speed underwater gun launcher developed by NUWC and General Dynamics Armament Systems (GDAS, formerly Lockheed Martin Armament Systems). This launcher was integrated with the NUWC-developed test range and instrumentation package.

The overall objective of this experimental program is a better understanding of supercavitating high-speed flight and stability in flows over a range of cavitation numbers, and over underwater Mach numbers from near zero through and exceeding unity. Quantitative measurements are made to determine the projectile velocity time history, projectile drag, projectile trajectory, and spatial and temporal characteristics of the cavity. Qualitative observations result in a better understanding of projectile stability and the cavity structure, including external shock waves.

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[1] These lecture notes are closely based on a previous publication by Hrubes, et al, (1998). The co-authors of that publication, J. Dana Hrubes, C.W. Henoch, C.M. Curtis, and P.J. Corriveau were essential to development of the information presented herein. They were supported in this effort by the NUWC Supercavitating High-Speed Bodies Test Team.

Paper presented at the RTO AVT Lecture Series on "Supercavitating Flows", held at the von Kármán Institute (VKI) in Brussels, Belgium, 12-16 February 2001, and published in RTO EN-010.

NUWC TEST FACILITY

The SHSB test facility is located at NUWC Division Newport. The tow tank is 49.4 m long by 6.1 m wide. The depth varies from 5.5 to 7.0 m. Its proximity to the research team makes it an ideal site for land-based high-speed undersea munitions and launcher testing. The range development task resulted in modification of this tank for the current program as well as for future SHSB programs.

The test hardware required to conduct the SHSB experiments was integrated with the test facility as depicted in the schematic diagram shown in figure 1. The underwater launcher is aimed to fire projectiles through 30.5 cm diameter holes in an array of armor baffle plates. Those projectiles that traverse the entire range are caught in a projectile catcher. If a projectile deviates more than about 15 cm from the nominal trajectory, the armor-plated baffle system stops the projectile and absorbs the energy so that it does not present a safety hazard.

Major hardware items include the underwater launcher system and mounting frame, projectiles, armor baffle plates, and a projectile catcher. Instrumentation includes witness screens, sensors and transducers, cameras (with enclosures and supports), video and analog data recorders, signal conditioners, a data acquisition and control computer, integrated circuitry, incandescent lamps, strobe lamps, a laser illumination system, and a launcher alignment system.

UNDERWATER LAUNCHER AND MOUNTING FRAME

The submerged gun launcher, or underwater firing fixture (UFF), currently consists of a 3.05m long, 30-mm smooth-bore barrel. The barrel diameter was chosen to accommodate the chamber pressures required to launch projectiles in excess of 1500 m/s. Prior to installing the smooth-bore gun, a 2.34 m long, 30 mm rifled GAU-8 Mann barrel was used. Figure 2 illustrates the gun assembly.

The gun is mounted in a box frame; this inner frame rides on rollers fixed to four rails, two above the frame and two below. These rails are mounted inside an outer frame that can be lowered in and out of the water while maintaining lateral position, and rests at the same position for every test firing. The inner frame rests against a heavy recoil plate that is hung aft of the frame. On firing, the inner frame moves aft along the rails within the outer frame, transferring no significant forces to the outer frame. The inner frame pushes the recoil absorption plate. The recoil velocity is decreased by acceleration of the mass of the plate, including the considerable added mass associated with fluid loading, while damping absorbs the recoil energy. A waterproof, pneumatically-operated breech with remote safe-and-arm features is screwed onto the end of the launcher barrel. High-pressure vents prevent damage to the barrel if it is fired when accidentally flooded. The gun launcher, mounted in the frame, is shown in figure 3.

To mitigate the effects of combustion gas ejection on the projectile cavity, the launcher bore is fitted with a 0.61m-long muzzle brake section of larger diameter, which allows the muzzle gases to expand before ejection into the free field. This decreases the pressure impulse on the projectile cavity, helping it to develop without transient collapse. The large-diameter muzzle brake also allows the cavity to develop behind the projectile without impinging on the face of the muzzle, further mitigating high transient launch pressures. In addition, the muzzle brake contains a sliding decelerator cylinder with a 21-mm hole to allow passage of the projectile. The remaining parasitic launch components are trapped by the decelerator, which exits the muzzle brake well after projectile passage.

A remote gun control unit allows the gun to be fired safely and initiates the computerized sequence critical to launch and data acquisition. At the discretion of the test director, the firing sequence can be aborted. The computerized sequencer starts the cameras and data recorders and activates capture and trigger mechanisms for cameras and stroboscopes.

PROJECTILE

Figure 4 is a photograph of the most successful projectile and sabot tested through December, 1998. The projectiles were designed in three phases. A concept design based on a semi-empirical model provided basic ballistics and hydrodynamics information. These results were refined using a mathematical model in a preliminary design cycle. Final design information was collected in a drawing package that included specifications of all dimensions, tolerances, and materials, along with precise estimates of mass properties.

The current projectile design has been developed through evolution over several years. Projectile materials have included maraging steel, tungsten, and titanium. Coupling materials have included aluminum, steel, titanium, and Ultem plastic.

PROJECTILE CONTAINMENT SYSTEM

The projectile containment system includes the armor plate baffle array and the projectile catcher. Armor plates roughly 1.22 m square by 2.54 cm thick with 30.5-cm holes are suspended every 1.52 m in the projectile path to provide effective termination of the projectile, should it travel off course. Each plate also has a 2.5-cm hole above the 30.5-cm hole to allow passage of a laser beam during plate alignment procedures.

A steel projectile catcher faced with a 1.22-m square baffle plate is suspended at the end of the array of armored baffle plates to stop those projectiles that traverse the entire range. The bucket is filled with steel plates, wood, and sand.

Since 1998, the range has been upgraded to extend the containment system (that is, the armor baffle plates) to the end of the tank, for a total length of approximately 45 m.

INSTRUMENTATION, CONTROL, DATA ACQUISITION, AND DATA PROCESSING

The range is instrumented to acquire both quantitative and qualitative data. Various launcher pressures are measured to assess launcher performance. Field pressures are measured to quantify perturbations due to the projectile, including any shock-wave system. The projectile displacement is measured using induction coils (for magnetized projectiles) or printed circuit break screens. Position, velocity, and drag are deduced from these measurements. Accelerometers measure motion of selected components in the tank. Induction coils and break screens are used to trigger components of various high-speed imaging systems.

Time and key range events are recorded by a computer-based data acquisition system and an analog tape recorder. Standard video and 35-mm cameras, a high-speed motion picture film camera, and high-speed intensified video imaging systems are available for each test. Illumination for each imager is provided by incandescent lamps, a copper vapor laser illumination system, or strobe lamps.

CONTROL AND DATA ACQUISITION COMPUTER SYSTEM

A desktop computer provides the platform for the data acquisition system. Data acquisition software configures two high-speed data acquisition boards, which control the data acquisition process in real time. The boards can each acquire up to 1.25 million samples per second, on up to eight differential channels. Each board has two analog timers and two digital channels, which are used to trigger other test functions such as camera shutters and the movie camera start signal, and which provide a reliable time basis for events throughout the duration of the test.

ANALOG DATA RECORDER

A 21-channel FM analog tape recorder is used as a backup for the computer data acquisition system. In the event that the computer fails to acquire some or all of the test data, the recorder is used to replay all data channels.

LAUNCHER PRESSURE AND MUZZLE VELOCITY SYSTEMS

Gas pressure at various locations in the launcher is measured by means of blast pressure transducers mounted in small ports in the barrel. Expected peak pressures are under 450 MPa in the chamber and under 70 MPa at the muzzle. Blast transducers are placed in the UFF to measure chamber pressure and pressure at various positions in the barrel. The blast transducer is a low-sensitivity, integrated-circuit, piezoelectric transducer with an output of 0.0102 mV per MPa and with high-pressure capability of more than 690 MPa. Two such sensors are screwed into the barrel velocity measurement holes to measure projectile velocity just before exit into the muzzle brake. The phasing between the pressure traces allow precise estimation of the projectile velocity.

UNDERWATER ACCELEROMETERS AND FIELD-PRESSURE TRANSDUCERS

Field-pressure sensors are mounted on a vibration-isolated rack downstream of the gun muzzle to measure dynamic pressure perturbations associated with passage of the projectile and shock system, if present. Acceleration of the recoil absorption plate and the first baffle plate are recorded by accelerometers mounted on those structures.

MOTION-DETECTION COILS

For tests where a magnetized steel projectile can be used, a voltage is induced by the magnetized projectile passing through a series of inductance coils for non-invasive velocity measurement. Velocity of the projectile is calculated using data from pairs of these coils. The coils are 45.7 cm in diameter and are mounted on a plastic post with the two active ends of the wire coil embedded and cabled to the instrumentation. The coils can also be used to trigger camera or illumination events.

BREAK-SCREEN MEMBRANES

Alternative velocity measurements are made using flexible mylar membranes on which continuous conductive circuits are printed. Each circuit is closed until broken by the projectile. These membranes double as witness screens, indicating projectile trajectory. Appropriate connecting circuitry was designed and assembled to produce signals for recording projectile velocity and for triggering instrumentation. When velocity coils are not used or the projectile is non-magnetic, break screens are mounted on each baffle plate to measure displacement and velocity.

WITNESS SCREENS

A system of witness screens is used to record the trajectory of each projectile during its passage downrange. Either mylar break screens or metal foils are mounted in frames. These frames are bolted to the containment baffles at known locations with respect to the nominal projectile trajectory. Pitch and yaw information can sometimes be deduced from the perforation shape.

GUN AND WITNESS-SCREEN ALIGNMENT SYSTEM

A laser bore-sighting technique is used for alignment of the launcher with the nominal trajectory. A blue-green laser enclosed in a waterproof housing is mounted securely to the gun barrel and co-aligned with the gun bore prior to each range alignment. The range is aligned by sighting the laser through 2.54 cm holes in each armor plate. The estimated cumulative error in the alignment of the range is +/-1.2 cm at the first plate and +/-1.8 cm at the tenth plate. In addition to range alignment, the 21-mm hole in the muzzle brake decelerator is aligned with the gun bore with an estimated accuracy of +/-0.03 cm.

CAMERA ENCLOSURES AND UNDERWATER PLATFORMS

Camera enclosures and support structures were fabricated to accommodate the cameras, the lights, and other necessary instrumentation. The enclosures are attached to platforms constructed of standard perforated metal framing, and are suspended at the desired depth and raised between tests for camera access. Other instrumentation, such as pressure transducers, are also attached to platforms. Cameras in close proximity to the gun muzzle are equipped with isolation-damped mountings to help protect the instruments from shock loading. Figure 5 illustrates some of the imager configurations.

IMAGING AND DATA ACQUISITION

Imaging and data acquisition at extremely high rates were critical to the success of this test program. This information has played a crucial role in post-test analysis leading to important design and operational changes. In addition, this information is important to the understanding of the physics of supercavitating bodies.

Imaging systems consisted of the following items: (1) Standard video (underwater and above water, full range coverage, incandescent lighting); (2) A high-speed 16-mm motion picture camera (10,000 frames/s, 15-W pulsed copper-vapor laser illumination, 100 ns pulse, front or shadow-graph lighting); (3) High-speed

gated, intensified video (incandescent or laser illumination); (4) 35-mm still cameras (front-lit, 50-mm lens, 3-µs front-lit stroboscope illumination); and, (5) 35-mm still cameras (50-mm lens, 3-µs shadow-graph stroboscope illumination). Each test used a variety of these imaging methods, but did not necessarily use all of them.

To use the resulting images for accurate measurements of cavity and projectile phenomena, image distortion must be assessed. The primary distortion issues are: (1) Optical distortion due to the flat window in front of the lens separating mediums of different indices of refraction; (2) Optical distortion of the image inside of a gas cavity in water; (3) Optical distortion due to movement of the projectile during the shutter or illumination period; and, (4) Camera lens distortion. Distortion sources 1 and 2 result primarily from the differences in the indices of refraction of the optical media: glass, air, and water.

TEST RESULTS

Over 50 projectiles were launched on the SHSB Test Range from the time the facility was completed through the end of the author's tenure at NUWC in December, 1998. Success criteria were based primarily on projectile performance and behavior. Calculated drag coefficient, stability of flight, and end-of-range residual kinetic energy were the major criteria. Results from each test have been used to guide an evolution leading toward an optimal design of the projectile and the launch package for the particular projectile configuration of interest. The primary projectile design parameters were the material (mass density), length-to-diameter ratio (aspect ratio), cavitator tip diameter, and overall shape (tail geometry, contour).

Figures 6 through 9 show several frames grabbed from some of the standard video cameras. Such single frames proved to yield a significant amount of important information regarding the projectile flight.

Figure 10 shows a sequence of shadow-graphs taken during one of the supersonic flights showing the shock wave produced in the water.

Figures 11 and 12 show two shadow-graphs captured using the 35-mm camera and a 3-µs stroboscope. These two images compare the flight of a normal and a damaged (hydrodynamically buckled) projectile as it passed the camera approximately 2.5 m from the gun muzzle exit.

Figures 13 and 14 show front-lit images captured using 35-mm cameras and 3-µs stroboscopes as the projectile reached a point approximately 5.5 m from the gun muzzle exit.

SUMMARY

A gun-launched underwater SHSB test range was constructed and has been used in extensive experimentation with supercavitating projectiles. Key results from this program have included the following:

- Successful design, construction, and operation of an indoor test range capable of launching supercavitating projectiles at velocities exceeding the speed of sound in water. In addition, an instrumentation and imaging suite has been integrated that provides the data necessary to perform basic research.
- Successful demonstration of fully submerged launch of supersonic, supercavitating projectiles at muzzle velocities up to 1550 m/s or Mach 1.03.
- Underwater, stable, subsonic and supersonic projectile flight has been demonstrated.
- Key parameters necessary for stable launch and flight have been identified.
- An understanding of launch dynamics has been acquired.
- Effects of varying projectile parameters and cavitator shape on subsonic and supersonic ballistics have been investigated.
- Good agreement of theory with experiment has been demonstrated.
- A tungsten projectile has been successfully launched underwater.

ACKNOWLEDGEMENTS

The material presented in this article was based on a previous publication (Hrubes, et al, 1998, listed in the references). In his role as Chief Engineer and Principal Investigator of the NUWC Supercavitating High-Speed Bodies program, the author of the current publication was supported by the NUWC Supercavitating

High-Speed Bodies Test Team led by Mr. J. Dana Hrubes, who served as Test Director. During various periods over the course of the program, Mr. C. Curtis and Dr. P. Corriveau served as Program Managers.

The author would like to acknowledge the sponsorship of the following organizations during the period discussed: the Office of Naval Research, the Defense Advanced Research Projects Agency, and the NUWC Division Newport In-House Laboratory Independent Research, Bid and Proposal, and Capital Purchase Programs. The enthusiastic guidance of the NUWC Technical Director, Dr. John Sirmalis, was essential to the success of this program.

Development of the current article was supported by Dr. Kam Ng (ONR), for which the author is especially grateful.

These lecture notes are dedicated to Prof. Yuri N. Savchenko and Mr. P. Kochendorfer, whose illuminating guidance in hydrodynamics and supercavitation has been inspirational.

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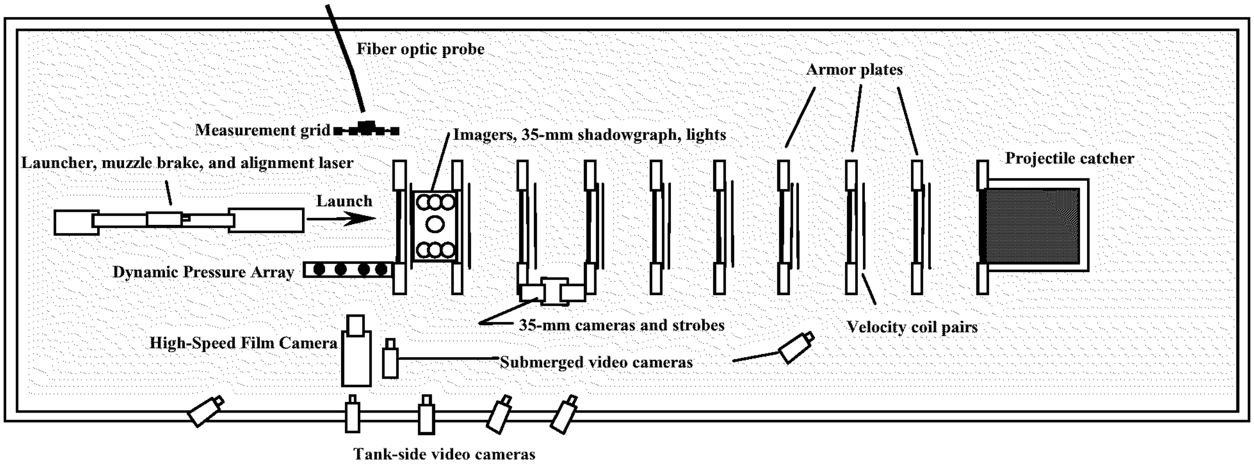

Figure 1. Schematic of SHSB test range

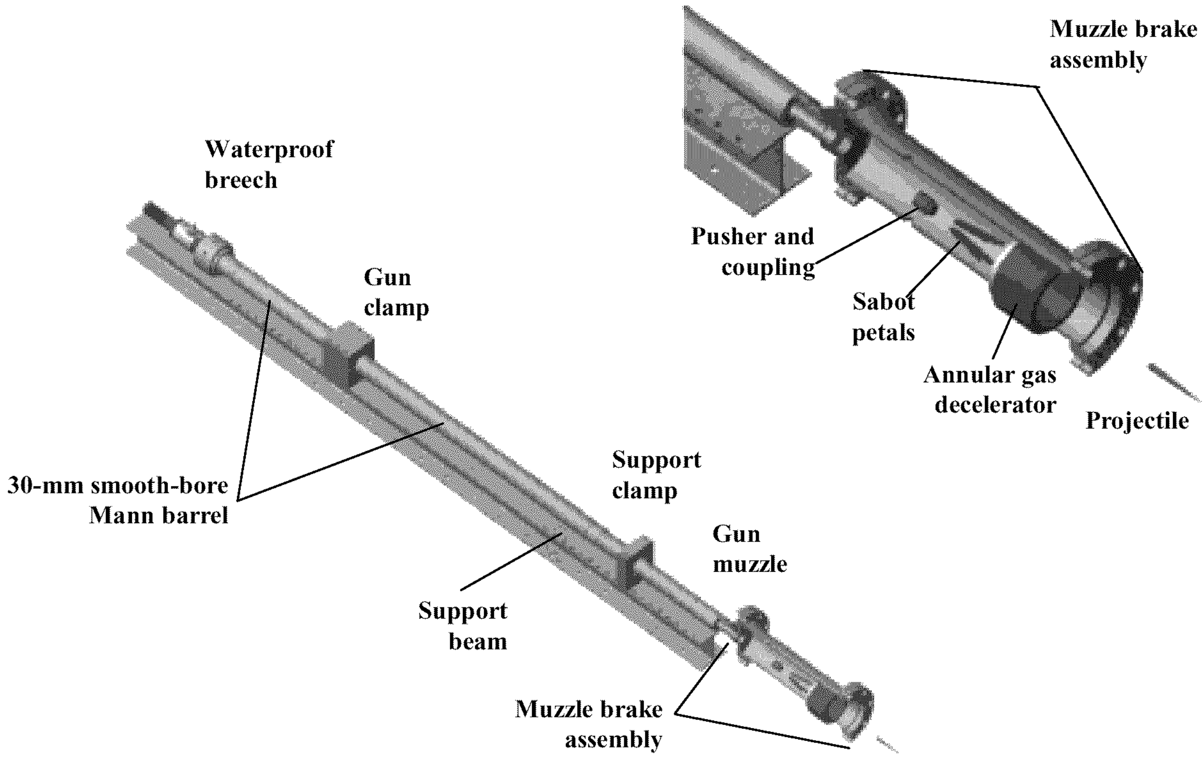

Figure 2. Schematic of 30-mm gun launcher and muzzle brake assembly

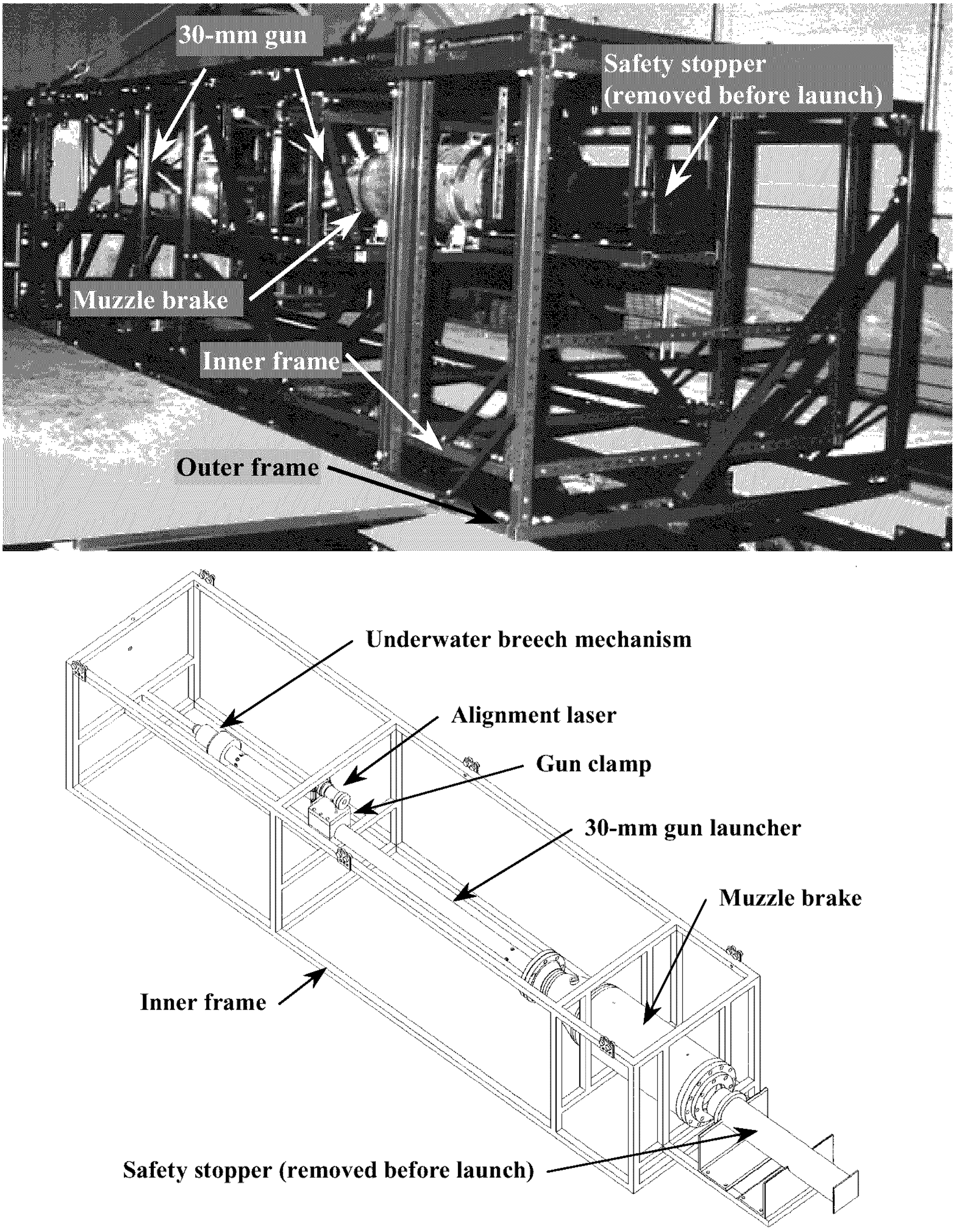

Figure 3. Photograph and schematic of launcher mounted in frame

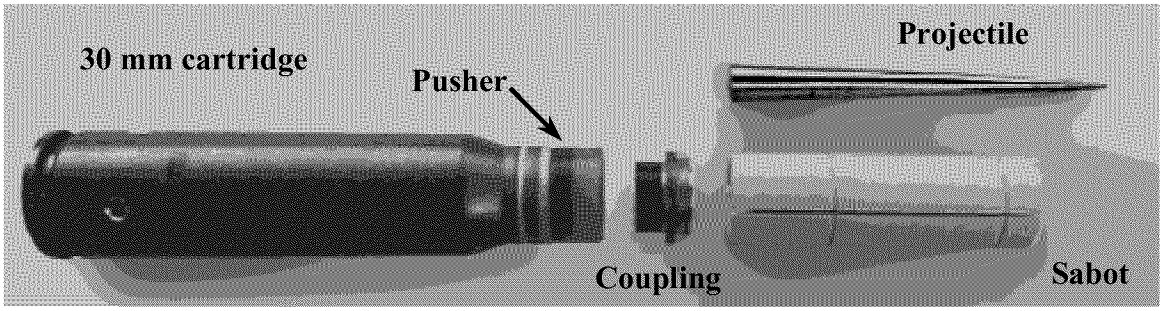

Figure 4. Successful 10:1 projectile launch package

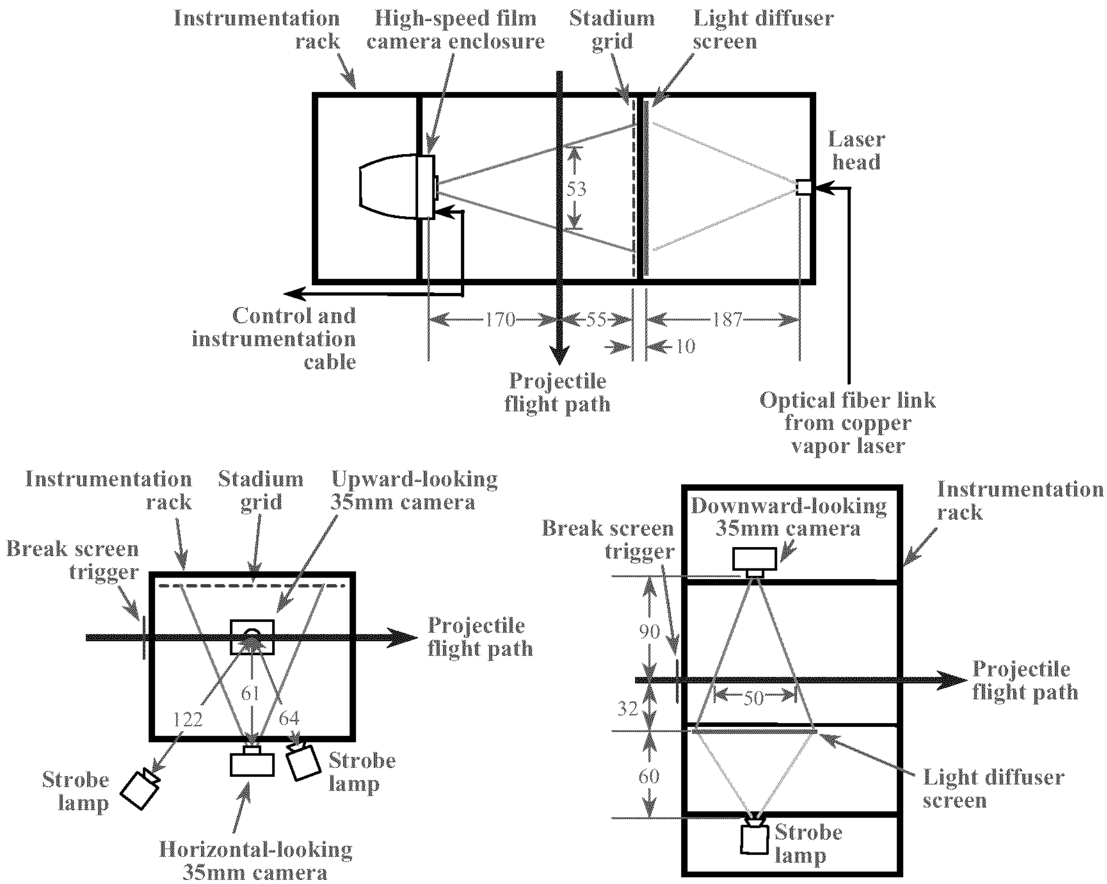

Figure 5. Various platform arrangements for high-speed imaging of projectile flight

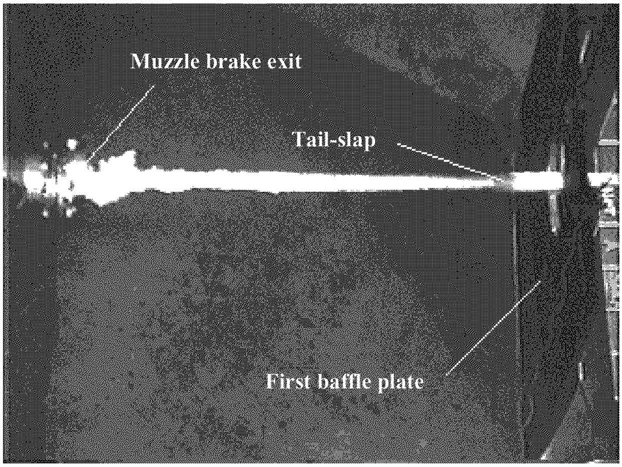

Figure 6. Projectile cavity – clean launch (standard front-lit video frame)

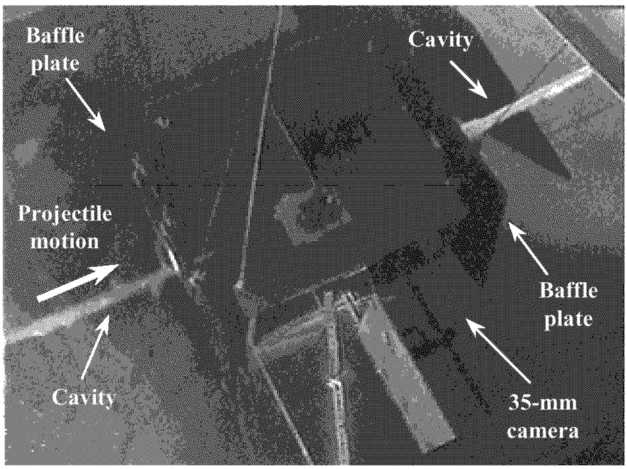

Figure 7. Projectile cavity – clean flight through instrumentation platform (standard front-lit video frame looking down)

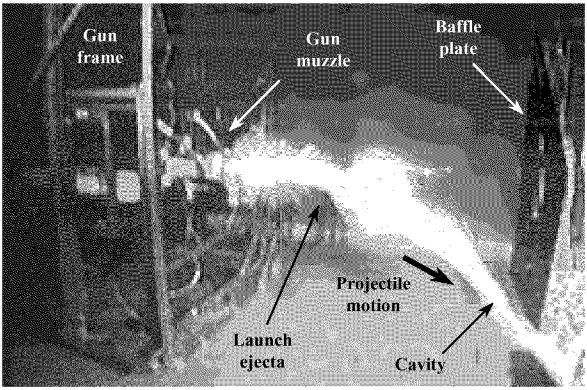

Figure 8. Projectile cavity – unstable flight (standard front-lit video frame)

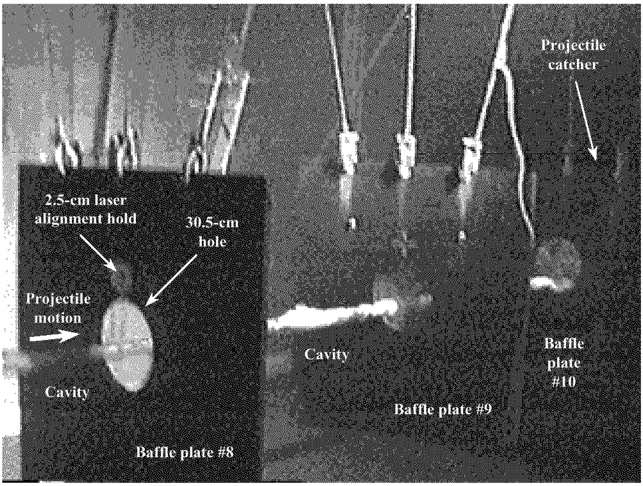

Figure 9. Projectile cavity – clean flight into catcher (standard front-lit video frame)

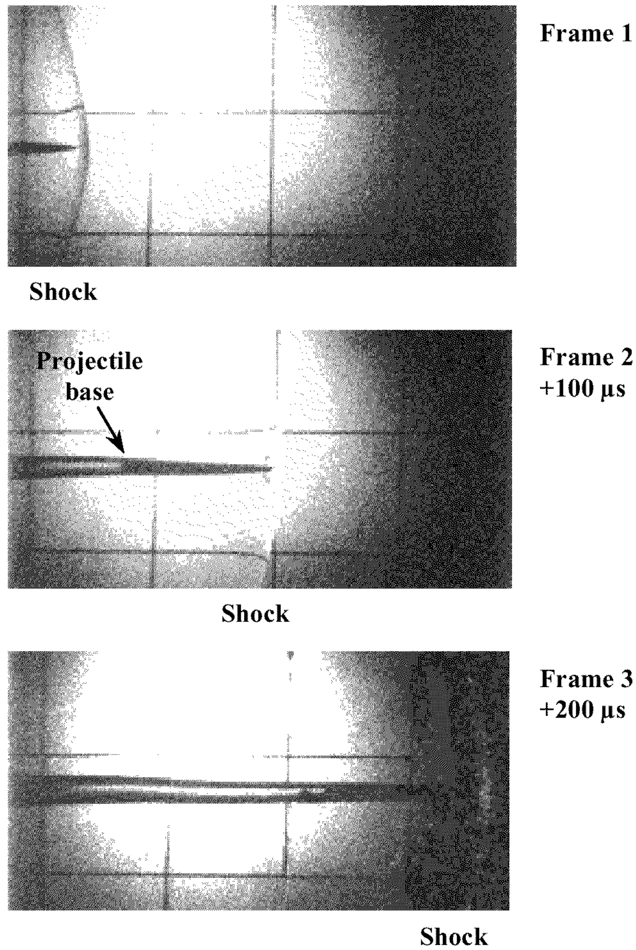

Figure 10. Projectile in supersonic flight (Mach number ~ 1.03; ~1549 m/s; high-speed shadow-graph film; 10,000 frames/s)

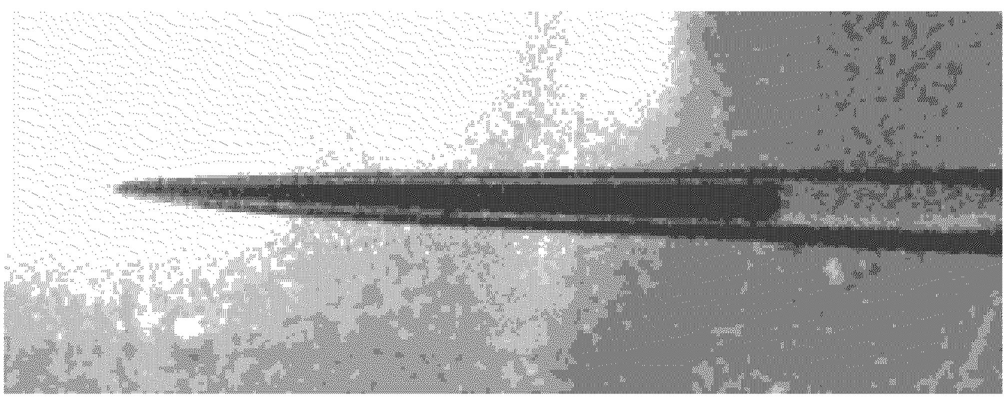

Figure 11. Projectile in cavity – clean flight (1200 m/s; 35-mm shadow-graph)

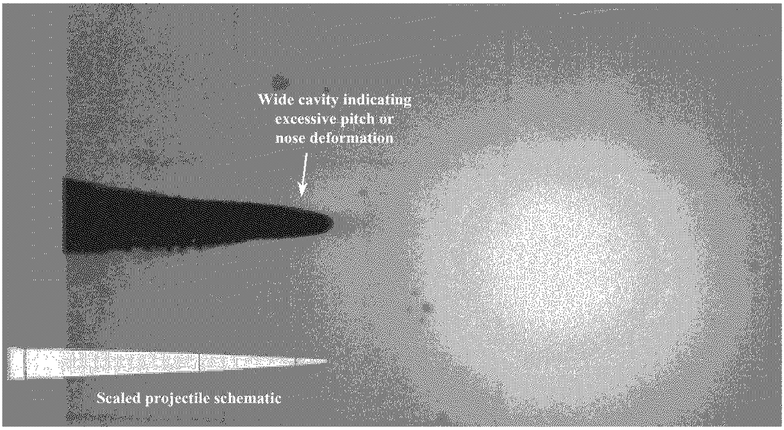

Figure 12. Projectile in cavity – damaged condition (35-mm shadow-graph)

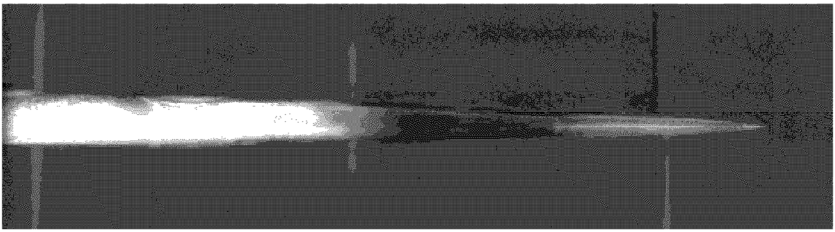

Figure 13. Projectile in cavity – clean flight (1200 m/s; 35-mm front-lit image)

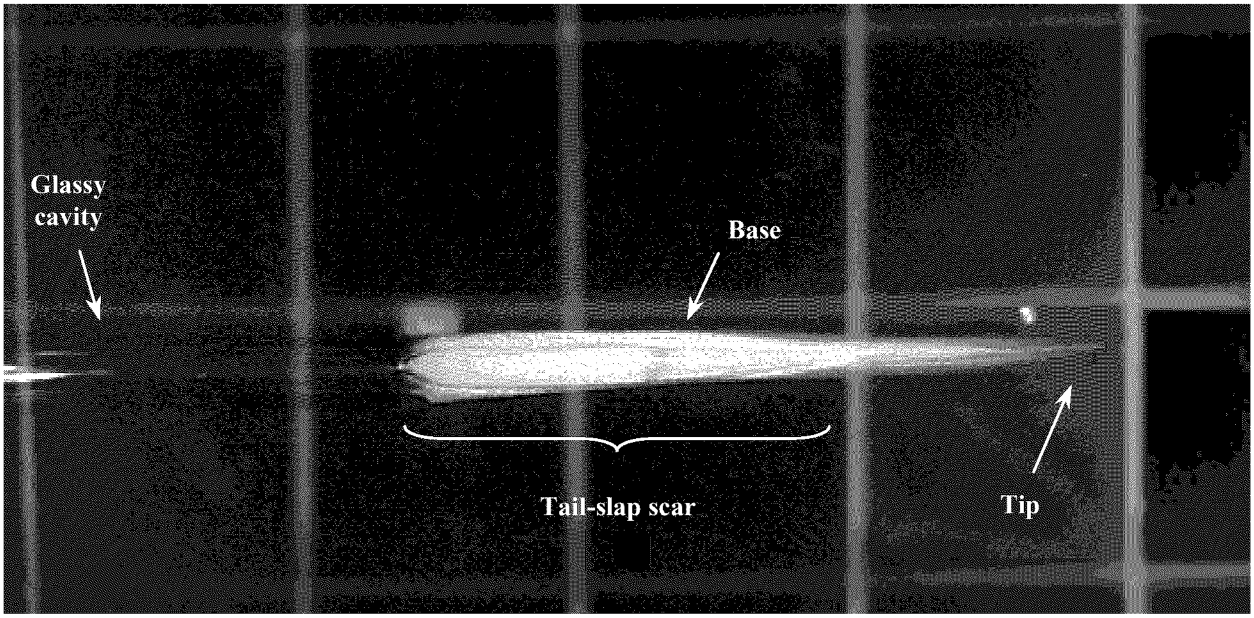

Figure 14. Projectile during a tail-slap event (1220 m/s; 35-mm front-lit image)